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DEMONSTRATION OF A TECHNIQUE FOR THE MEASUREMENT OF SURFACE PRE--ETC(U)
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MEMORANDUM REPORT ARBRL-MR-03017

DEMONSTRATION OF A TECHNIQUE FOR THE MEASUREMENT OF SURFACE PRESSURES ON SPINNING WIND TUNNEL MODELS VIA TELEMETRY

William P. D'Amico, Jr.

April 1980

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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1. REPORT NUMBER MEMORANDUM REPORT ARBRL-MR-03017	2. GOVT ACCESSION NO. AD-A086 845	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) DEMONSTRATION OF A TECHNIQUE FOR THE MEASUREMENT OF SURFACE PRESSURES ON SPINNING WIND TUNNEL MODELS VIA TELEMETRY		5. TYPE OF REPORT & PERIOD COVERED Final
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) William P. D'Amico, Jr.		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS US Army Ballistic Research Laboratory ATTN: DRDAR-BLL Aberdeen Proving Ground, MD 21005		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS RDT&E No. 1L162618AH80
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Armament Research & Development Command US Army Ballistic Research Laboratory ATTN: DRDAR-BL Aberdeen Proving Ground, MD 21005		12. REPORT DATE April 1980
		13. NUMBER OF PAGES 33
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

DISTRIBUTION STATEMENT A
Approved for public release;
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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Telemetry
Magnus
Pressure Distribution
Wind Tunnel
Transducers

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The measurement of surface pressures on rotating bodies such as wind tunnel models or spin-stabilized projectiles is possible through the use of a telemetry link. Via telemetry, the rotating and/or translating frame can be coupled to the laboratory or stationary frame, but great care must be exercised to properly account for differences in phase within the various data channels. A novel and unique pressure measurement was accomplished by Mark for a spinning wind tunnel model, but the circumferential pressure distributions contained an anomalous phase error. This error has been identified and corrected. A phase

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20. delay was produced by a low pass filter used in the discrimination of the output of the telemetry receiver. Since the receiver output had been recorded in an analog form, some of the original data were re-reduced with corrections for a constant phase delay. With the phase anomaly explained, the original technique of Mark presents a very attractive scheme for the acquisition of surface pressure data from spinning models.

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I. INTRODUCTION

The measurement of surface pressures on rotating bodies such as wind tunnel models or spin-stabilized projectiles can be accomplished through the use of a telemetry link. Mark utilized miniature pressure transducers and a telemetry link to measure surface pressures on a spinning, wind tunnel model.[1] The data gathered by this technique were contaminated by an error in phase, thus damaging the credibility of the data and the experimental method. The phase error was produced by a low pass filter used in the discrimination of the output from the telemetry receiver. Some of the original data have been re-reduced with appropriate phase corrections, and they are in general agreement with accepted physical principles. This report serves to explain and remove the original phase error and to comment on the feasibility and potential of the measurement technique.

II. REVIEW OF THE ORIGINAL EXPERIMENT BY MARK

A brief review of the experiment by Mark considers the model, circuitry, run conditions, and data.[1] The model was a 5.715 cm diameter, 7.1 caliber tangent-ogive-cylinder with a 3 caliber nose, as shown in Figure 1. Two pressure transducers located on the spin axis of the model were ported to the exterior of the model. The ports were 180° apart and located 3.14 calibers from the nose. The model was spun up to 333 Hz (20,000 RPM), the air was shut off, and the model was allowed to slowly spin down. Good data were obtained at Mach numbers of 2.0, 2.5, and 3.5 at angles of attack of 0.0, 4.20, 8.48, and 10.62 deg. A block diagram of the transducers, amplifiers, and the telemetry link are shown in Figure 2. The output of one transducer was amplified and fed directly to a 70 kHz subcarrier. The output of the second transducer was amplified and differentially combined with the first transducer to produce a pressure difference. Only data from the 70 kHz subcarrier were re-reduced. A combined pressure and subcarrier oscillator calibration is given in Figure 3. This calibration was done prior to final assembly and potting. The final calibration for the model could not be found or reconstructed, and differences in pressure amplitude between the data of Reference 1 and data presented in this report will exist. Such differences are bothersome, but are not considered to be significant in light of the phase errors that have been uncovered and explained. A typical plot of the original data from Reference 1 is shown in Figure 4. The angle

1. *A. Mark, "Pressure Measurements on a Spinning Wind Tunnel Model by Means of Telemetry," U.S. Army Ballistic Research Laboratory Memorandum Report No. 2750, May 1977. AD A040909.*

ϕ determines the orientation of the port leading to the 70 kHz pressure transducer. In the reference system of the wind tunnel, a phase angle, ϕ, locates the roll angle of the model. $\phi=0$ is vertically down. The model was set at an angle of attack, α, vertically upwards. Physical principles dictate that the maximum pressure should be on the windward side of the model at $\phi=0$. The data show that the maximum pressure occurs at $\phi=0$ only when the spin approaches zero. A phase shift was computed from the difference between the angle at which maximum measured pressure occurs and $\phi=0$. This phase shift is shown in Figure 5 (from Reference 1) and indicates that the shift increases linearly with spin.

III. RE-REDUCTION OF DATA

A. Determination of Magnitude and Phase

The accuracy of calibration of a pressure measurement system utilizing a telemetry link can be significantly improved by the determination of the transfer function of the complete measurement system. A separate calibration must be performed to determine the gage factor of the pressure transducer. The transfer function is a complex quantity and therefore has two components. The real part gives the relative magnitude between the output and input signals, while the imaginary part gives the phase delay of the output with respect to the input signal. This method of calibration is far superior with respect to that shown in Figure 3. Transfer function measurements should be repeated and logged for future reference and will allow small variations in the system calibration to be monitored routinely, thereby providing greater measurement accuracy. Also, the measurement of gain and phase delay are accomplished simultaneously. Since the measurement of phase is central to the data that will be discussed, a short review is provided for the case of a low-pass filter commonly used in the discrimination of an FM/FM telemetry signal. The time delay produced by these filters is important since it has a direct bearing on the dynamic accuracy of the system. It would be desirable to have a constant delay. Under such circumstances, all frequencies would be delayed by the same time constant and no distortion of the signal would occur. This ideal case cannot be achieved in general, but it can be approximated.[2] For example, suppose a network has a transfer function $H(S) = Ae^{-\tau S}$, where τ and A are constants. If the excitation and the response to the network are E(t) and R(t) with Laplace transforms E(S) and R(S),

2. *Richard G. Vorce, "Filter Characteristics," EMR Telemetry Application Note, Sarasota, Florida.*

then, $E(S) \longrightarrow H(S) \longrightarrow R(S).$

In the frequency domain the transfer function becomes

$$H(j\omega) = Ae^{-j\omega\tau},$$

where the magnitude and phase are $M(\omega) = A$ and $\theta(\omega) = -\omega\tau$. For this model the phase is linear with frequency, and the response of such a network is

$$R(S) = AE(S)e^{-\tau S}.$$

The inverse transform is

$$R(t) = AE(t - \tau)\mu(t - \tau),$$

where $\mu(t - \tau)$ is a delta function. This response shows there is a time delay of τ. To identify that time delay, we find

$$t_D = \tau = -\frac{d\theta(\omega)}{d\omega}$$

Hence, the derivative of the phase of the transfer function with respect to frequency yields the time delay for a linear delay system.

In practice, one finds that phase delays are large but linear in frequency for ω less than 1 kHz and small but nonlinear for ω much larger. The frequency range of interest for the pressure data is DC to 333 Hz. A low pass data filter would typically be set at three or four times the highest frequency present within the data, or for the experiments of interest at approximately 1 kHz. The phase delay produced by the telemetry system, the receiver, and the tape recorder should be small since these systems employ wide band filters.* In an attempt to correct the data, it was assumed that the major portion of the time shift of Figure 5 was produced by discrimination and low pass filtering of the pressure data. This can be easily reproduced. A white noise source was fed to a 70 kHz signal which was then discriminated at several settings for the low pass filter within the discriminator. The output of the discriminator was fed to a spectrum analyzer that is capable of resolving the phase and magnitude of the transfer function of the network. Filter settings of 10.5, 1, and 0.7 kHz resulted in phase delays of 67.7 μs, 0.496 ms, and 0.75 ms. Figure 6 shows the phase of the transfer function for a 1 kHz setting on the discriminator. This time delay at 20,000 RPM produces a phase shift of approximately 60 deg. The phase angle in Mark's data for this speed (Figure 5) is approximately 75 deg.

* *It is not possible at this time to reconstruct the time delay due to these networks, and the measurements of phase are still in error by this omission.*

In an attempt to determine possible phase errors in the measurement system, Mark also performed a test with the wind tunnel/telemetry model in a vacuum chamber. The chamber was fitted with a tube which was directly fed onto the surface of the spinning model at the location of the pressure transducer tap. Hence, a data record showing the time between successive pulses from the pressure transducer and the coul used for the measurement of spin could be combined with the instantaneous spin to check for a phase shift. Original data measurements using this technique showed no clear evidence of a phase shift. However, the data were re-reduced, and the new reduction indicated a phase shift that correlates well with the phase shift measurement due to the low pass filter.

The pressure data presented within this report was digitized by a Nicolet Explorer Digital Oscilloscope Series 2090. The data were then transferred to a Hewlett-Packard 9845 Computer for conversion to engineering units and final plotting. A typical digital trace of the pressure and spin data channels versus time is shown in Figure 7. Channel A provides the pressure data, while Channel B gives the timing marks from a coil and magnet. The inverse of the time between the pulses on Channel B provides the spin rate of the model. The pressure signals are inverted by the onboard electronics, i.e., a minimum voltage corresponds to a maximum pressure and locates $\phi=0$ approximately. The actual location of $\phi=0$ is accomplished in the following manner. Figure 8 shows a section of the wind tunnel model with the locations of the magnet, coil, and the pressure port for the 70 kHz pressure transducer. A spin pulse is produced at this orientation since the magnet and coil are aligned. The port for the 70 kHz transducer will then be located at $\phi=220$ deg, but the pressure data are delayed due to the low pass filter within the discriminator. This delay is 0.496 ms, which for the data within Figure 7 (the spin is 12,195 RPM) translates into an angle of 36.3 deg. Hence, the phase of the pressure signal is actually 183.7 deg at the time a spin pulse is generated. This is consistent with the data in Figure 7 since the spin pulses and maximum pressure voltages (minimum pressure due to inversion by the electronics) occur at the same time.

During the re-reduction of the data, the center frequency of the discriminator was off-set so as to center the time-varying portion of the pressure signal within the appropriate voltage scale of the digitizing oscilloscope. This technique allows for greater resolution. The DC off-set was measured, translated into pressure with the calibration data of Figure 3, and recombined with the time-varying portion of the signal after digitization.

B. Zero Degrees Angle of Attack

Data were reduced at zero angle of attack to determine the sensitivity of the transducers and the port networks to spin. Three Mach numbers were considered: 3.5, 2.5, and 2.0. No dependence on spin was observed for any of the data runs. The raw voltages for Mach 3.5 are shown in Figures 9 and 10 for spins of 17,595 and 7,159 RPM, respectively. For zero angle of attack, the pressure distribution around the model should be independent of spin, and the data show variations of ±5 mv, or approximately 275 Pa or 0.04 psia.

C. 10.62 Degrees Angle of Attack at Mach 3.5

Data were reduced for several spin rates. Shown in Figure 11 are the pressure voltages for a spin of 16,565 RPM. The data are smooth and periodic, and the flow is apparently steady. Figure 12 provides a superposition of pressure data at three spin rates. The trace for 16,595 RPM indicates the maximum pressure to be at ϕ=15 deg. This apparent phase shift may be due to unrecoverable phase delay in the amplifier/telemetry/tape recorder system. The asymmetry in the pressure distribution on the leeward side of the model (ϕ=180 deg) is produced by spin.

D. 4.2 Degrees Angle of Attack at Mach 2.0 and 3.5

All of the data at an angle of attack of 4.2 deg were dramatically different from either the 8.48 or 10.62 deg data. The pressure distributions were unsteady for all Mach numbers and all spin rates. It is highly probable that a model vibration was present. It is unlikely that the electronics were faulty since the tests were performed by fixing a Mach number and varying the angle of attack from zero to 10.62 deg. In all cases, only the data at 4.2 deg were unsteady. Traces of the raw pressure-related voltages are shown in Figure 13 for Mach 2. The pressure distribution on the leeward side of the model was unsteady, and the maximum pressure on the windward side of the model also varied in amplitude. Figure 14 shows the pressure distribution for Mach 3.5 at 13,544 RPM. The discontinuity in the data at ϕ=180 deg is produced by the unsteady behavior previously discussed. If the pressure distribution were periodic, no discontinuity should exist. Figure 15 shows two successive cycles of pressure superposed and indicates the magnitude of the unsteady part of the pressure. It is clear that both the leeward and the windward sides of the model are affected. The influence of spin on the shape of the pressure distribution is obscured by the unsteady nature of the data.

IV. DISCUSSION

The use of telemetry links for the measurement of physical phenomena on board free-flight projectiles is well known. Temperature and pressure histories have been measured in the interior of chemical payloads.[3,4] Surface pressure measurements have been made on gun-launched cones by Mark.[5] Also, recent measurements of inertial wave pressures in a rotating cylinder were accomplished by Whiting.[6] Surface pressure measurements on wind tunnel models have been made by Miller.[7]

Although modern computational techniques have made many advances, there are situations where pressure measurements would be of great value. For example, flows with complex viscous interactions at large angles of attack cannot be computed. Also, some geometric shapes are not tractable to computational schemes. This often occurs when small surface irregularities or protuberances are present.

The accurate measurement of surface pressures on rotating bodies is difficult, since high resolution is required. For example,

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3. *W.H. Clay, W.P. D'Amico, A. Mark, and W.H. Mermagen, "Measurements of Payload Temperature On-Board the XM687 155mm Binary Projectile," Ballistic Research Laboratories Memorandum Report No. 2508, July 1975. AD B007023L.*

4. *W.P. D'Amico, W. H. Clay, A. Mark, and W. H. Mermagen, "In-Flight Payload Temperature Measurements for the XM736 Binary Projectile," U.S. Army Ballistic Research Laboratories Memorandum Report No. 2560, November 1975. AD B008702L.*

5. *A. Mark, "Free-Flight Base Pressure Measurements on 8° Cones," U.S. Army Ballistic Research Laboratories Technical Report ARBRL-TR-02179, July 1979. AD A075365.*

6. *R.D. Whiting, "An Experimental Study of Forced Asymmetric Oscillations in a Rotating Liquid-Filled Cylinder," U.S. Army Ballistic Research Laboratories Report in publication.*

7. *Miles C. Miller, "A Magnetic-Fluid Seal for Measurement of Aerodynamic Surface Pressures," Chemical Systems Laboratory Technical Report ARCSL-TR-77018, April 1977. AD B034-708.*

pressure differences that produce Magnus effects are often as small as 70 Pa (0.01 psi). It seems straightforward to simply locate pressure transducers directly on the surface of a spinning model. However, one must then account for the effects of centrifugal force on the calibration of the transducer. The transducers used by Mark and Whiting were semiconductor, integrated sensors mounted on a diaphragm. The acceleration sensitivity of these units is typically 0.0005% FS/g* perpendicular to the diaphragm and 0.0001% GS/g parallel to the diaphragm. For the wind tunnel model used by Mark (5.715 cm in diameter with a maximum spin of 20,000 RPM), the calibration would have been off-set by 6% of full scale if the transducers had been located on the side wall of the model. Mark chose to locate the transducers on the centerline, i.e., the spin axis of the model, and to use ports. Questions of frequency response and phase delay of the ports must be answered, and these questions may be more difficult to resolve than those of the centrifugal effects. Centrifugal effects produced by spin and angular motions could be simulated by a coning motion device. The calibration of the transducer could then be corrected for these accelerations. Overpressures are also of great concern, especially in gun-launched experiments. The transducers used by Mark[5] and those used by Whiting[6] were built with a metal stop behind the diaphragm and provide a maximum over-pressure ratio of 40. Experience with these transducers has shown the sensitivity to be almost infinite. The resolution of the transducers seems to be limited only by the calibration accuracy. Calibration data are very linear when the transducer output is as small as 0.2% of full scale (10 mv). To further assess the factors of resolution, accuracy, and linearity, calibrations should be attempted at much more sensitive levels. If these calibrations are successful, the resolution in pressure may be well below 70 Pa (0.01 psi). In circumstances where high resolution is required, other factors must be re-examined. For example, the output of these transducers is proportional to the excitation voltage. Therefore, the stability of the excitation voltage must be high and should be monitored continuously. Also, the resolution and accuracy of an FM/FM telemetry system i limited by the discrimination procedure. Typically, the resolution of a discriminator is 0.1% of full scale. This level (approximately 0.2% FS for the transducers used by Mark) severely limits the extension of the measurement technique to lower pressures. In these instances a pulse code modulation (a digital encoding) telemetry system may be required. Miniature PCM devices are commercially available and should be evaluated.

V. CONCLUSIONS

A technique for the measurement of surface pressures via telemetry on spinning wind tunnel models or spin-stabilized projectiles has been demonstrated. An initial attempt was successful in measuring surface pressures on a wind tunnel model, but an error in phase was produced

* *Full scale per g, where g is the acceleration due to gravity.*

by discrimination and filtering of the output of the telemetred data. The error was identified and corrected. The resolution and quality of the data for these tests were very good. Pressures as small as 70 Pa (0.01 psi) could easily be resolved.

REFERENCES

1. A. Mark, "Pressure Measurements on a Spinning Wind Tunnel Model by Means of Telemetry," U.S. Army Ballistic Research Laboratory Memorandum Report No. 2750, May 1977. AD A040909.

2. R.G. Vorce, "Filter Characteristics," EMR Telemetry Application Note, Sarasota, Florida.

3. W.H. Clay, W.P. D'Amico, A. Mark, and W. H. Mermagen, "Measurements of Payload Temperature On-Board the XM687 155mm Binary Projectile," Ballistic Research Laboratories Memorandum Report No. 2508, July 1975. AD B007023L.

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6. R.D. Whiting, "An Experimental Study of Forced Asymmetric Oscillations in a Rotating Liquid-Filled Cylinder," Ballistic Research Laboratories report in publication.

7. Miles C. Miller, "A Magnetic-Fluid Seal for Measurement of Aerodynamic Surface Pressures," Chemical Systems Laboratory Technical Report ARCSL-TR-77018, April 1977. AD B034-708.

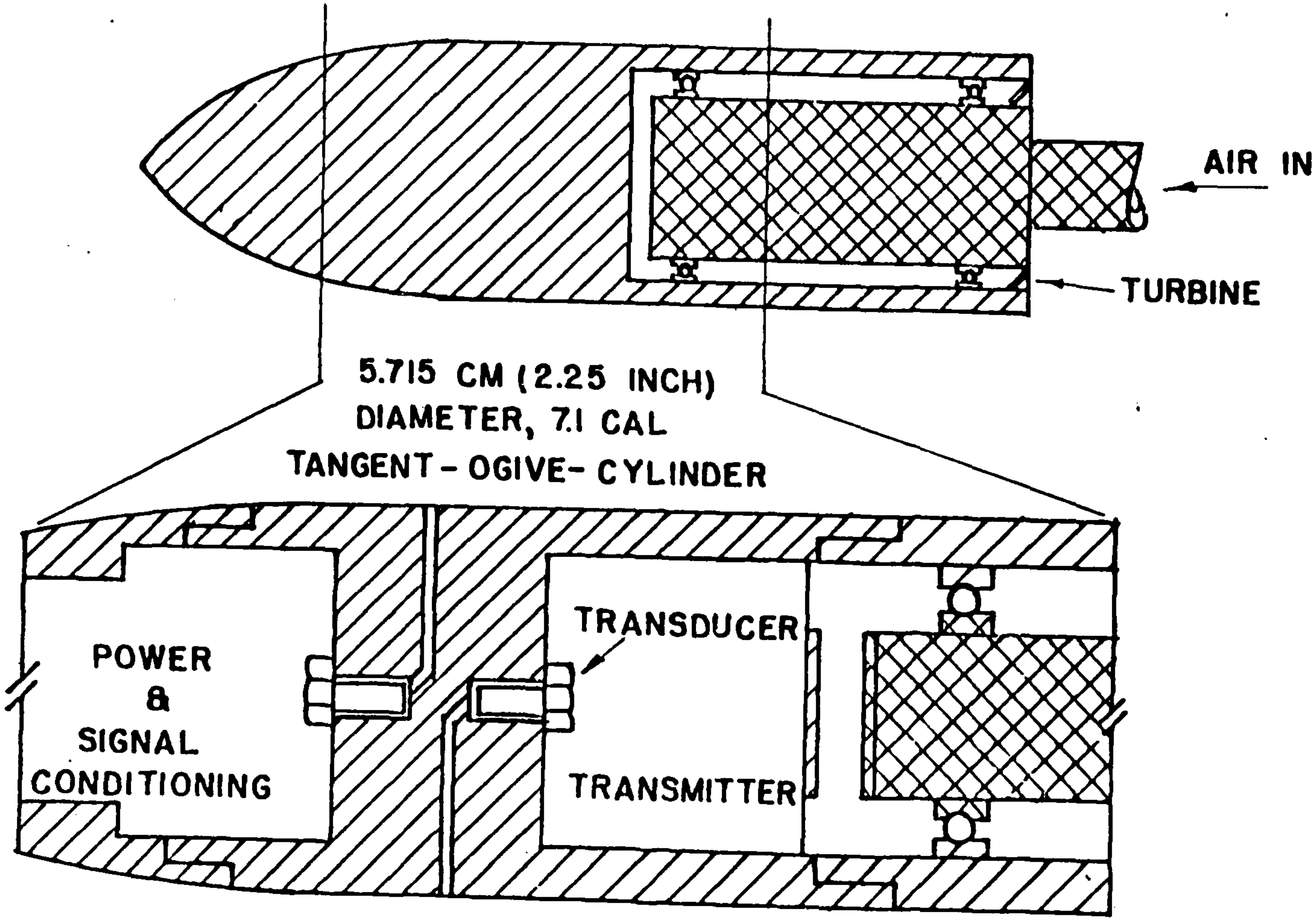

Figure 1. Cutaway Schematic of Magnus Telemetry Model (Reference 1)

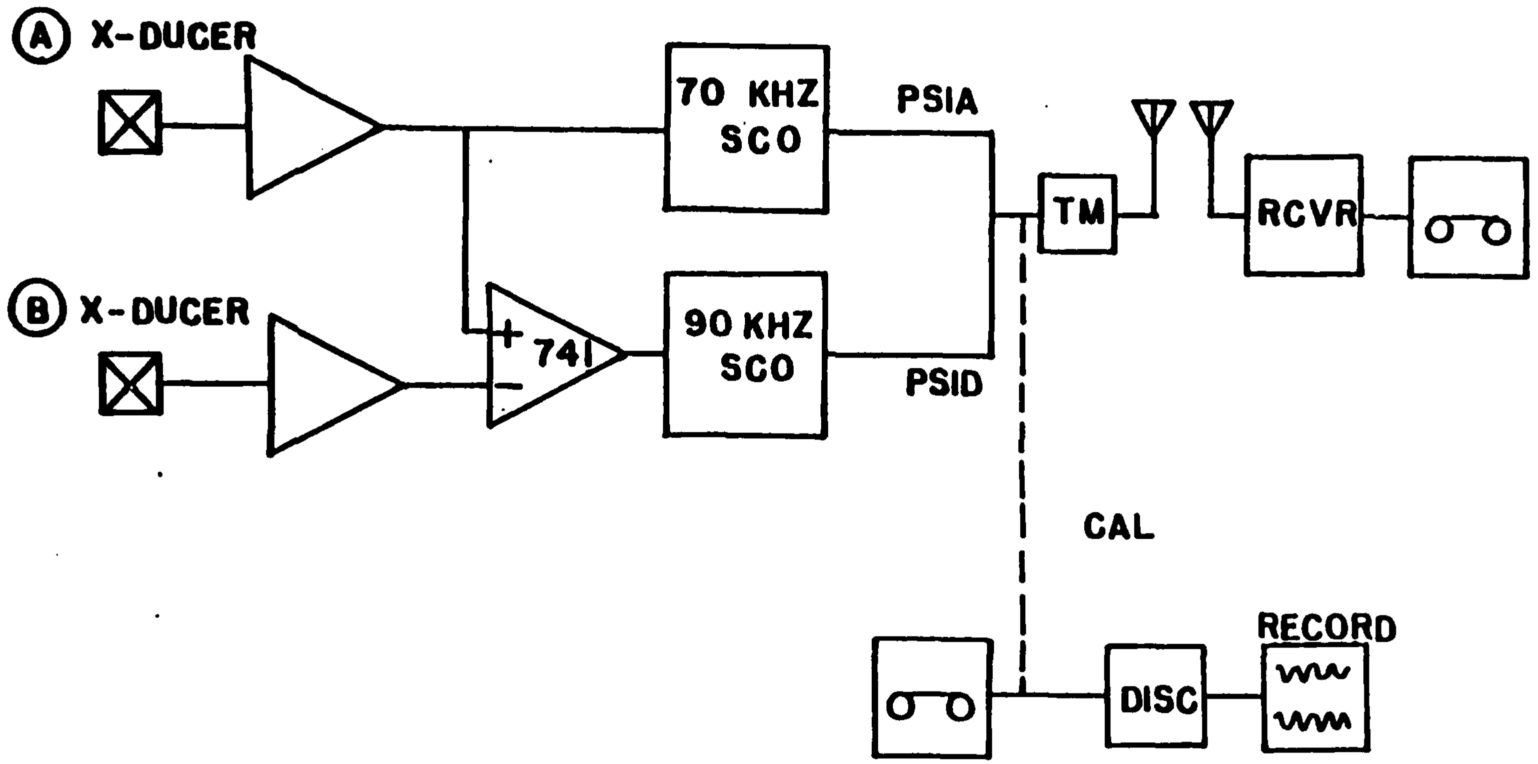

Figure 2. Block Diagram of Transducer/Amplifier/Telemetry System (Reference 1).

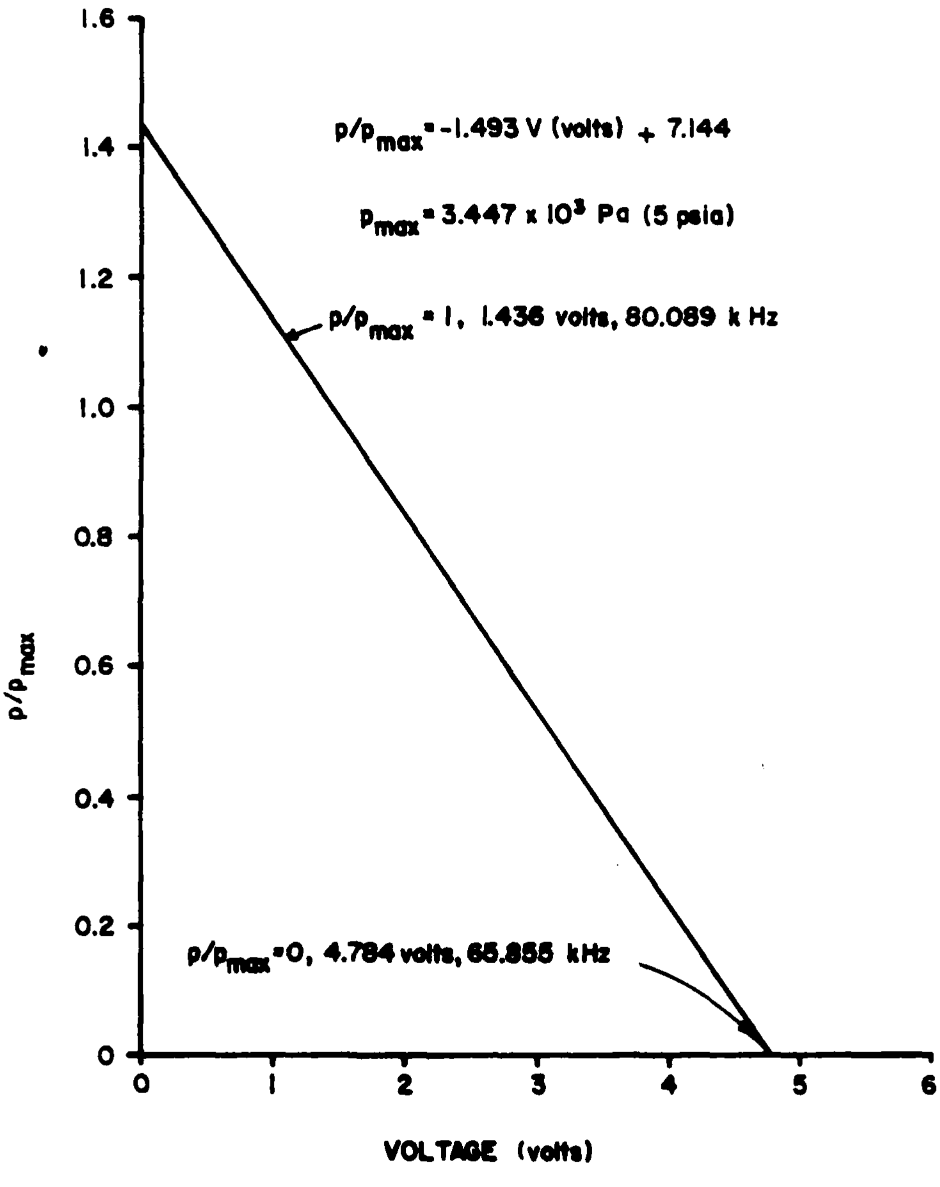

Figure 3. Combined pressure and subcarrier Oscillator Calibration.

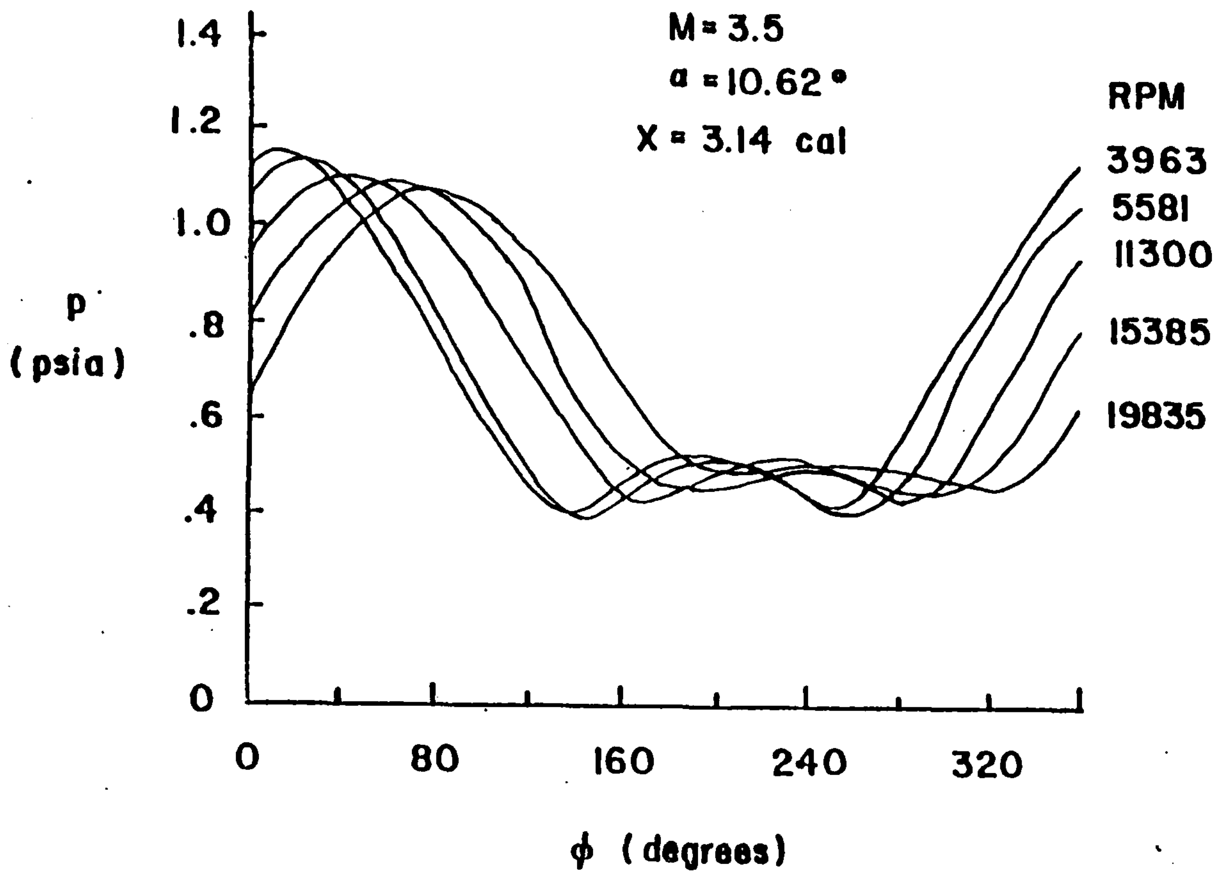

Figure 4. Surface Pressure Distribution on Tangent-Ogive-Cylinder Model with Spin (Reference 1)

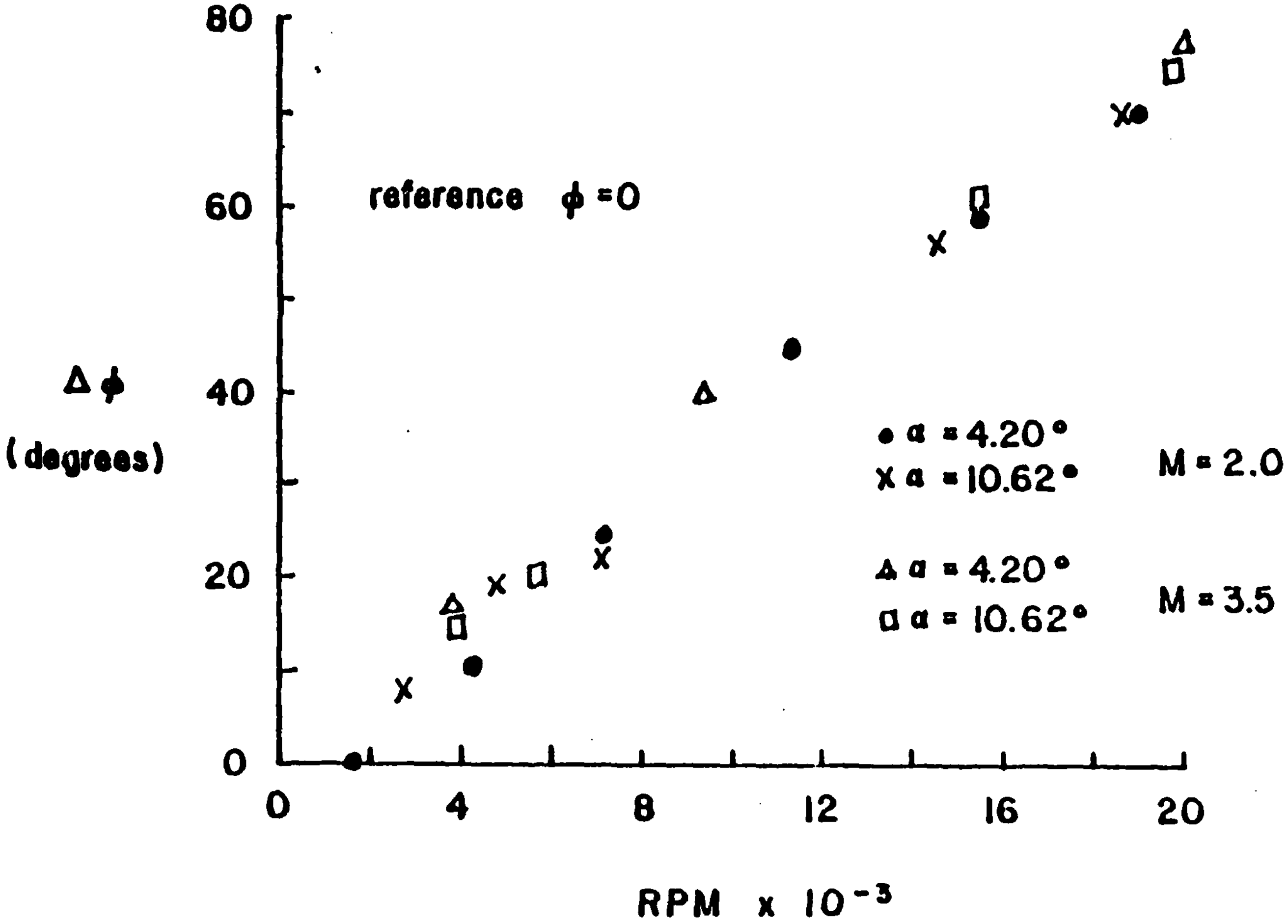

Figure 5. Graphical Display of Peak Pressure Shift in Rotating Wind Tunnel Model (Reference 1)

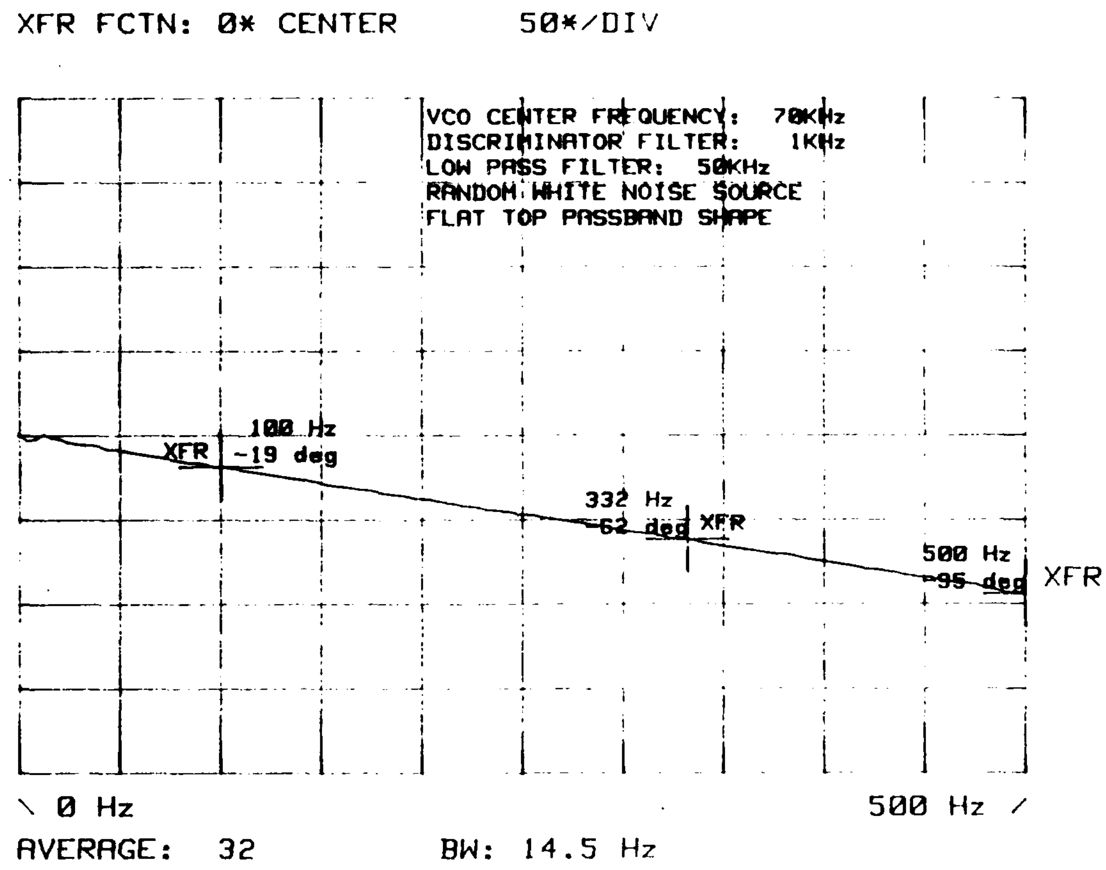

Figure 6. Imaginary part of the Transfer Function for a Discriminator with a 1 kHz low pass filter.

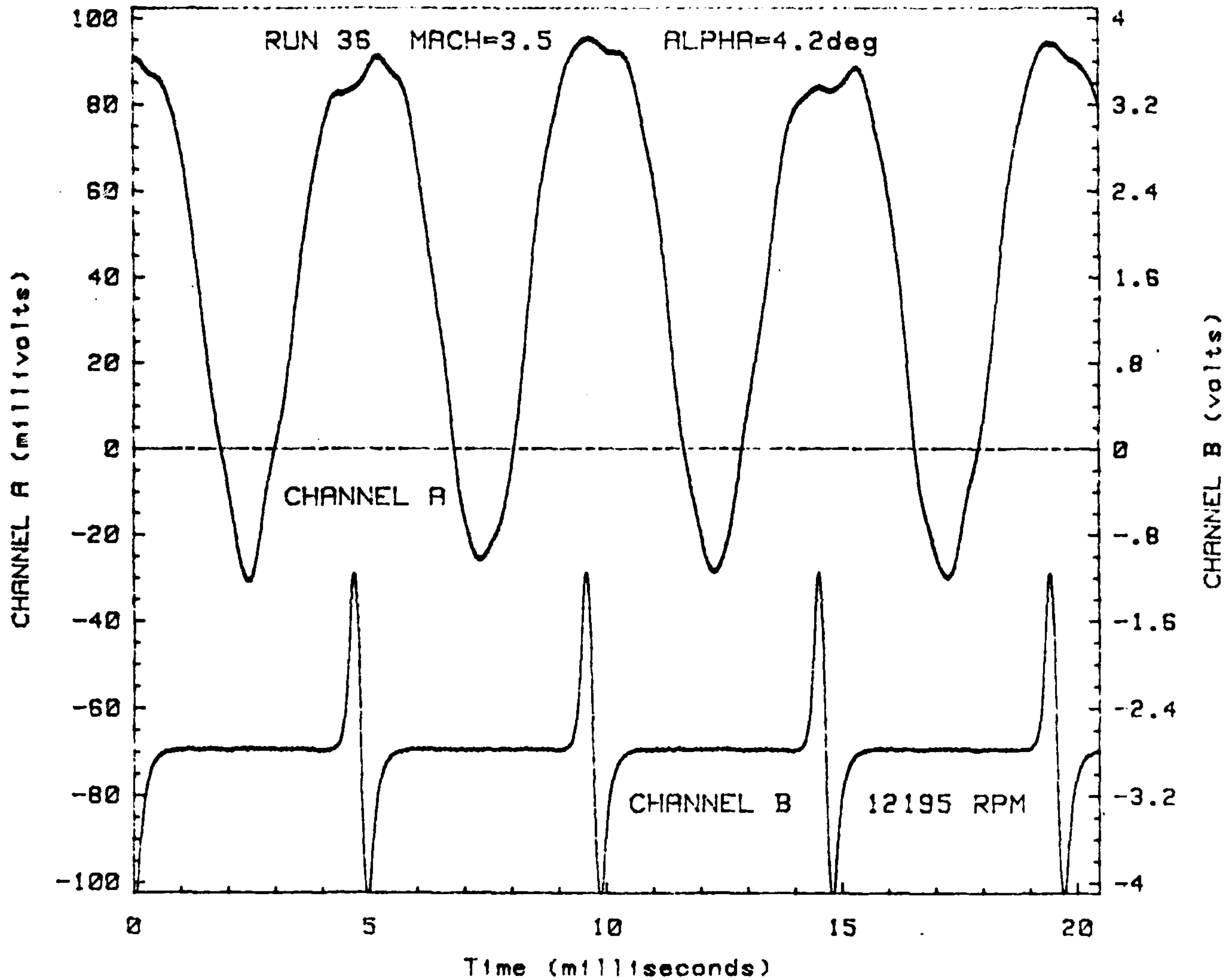

Figure 7. Typical raw pressure and spin voltages from the digital oscilloscope.

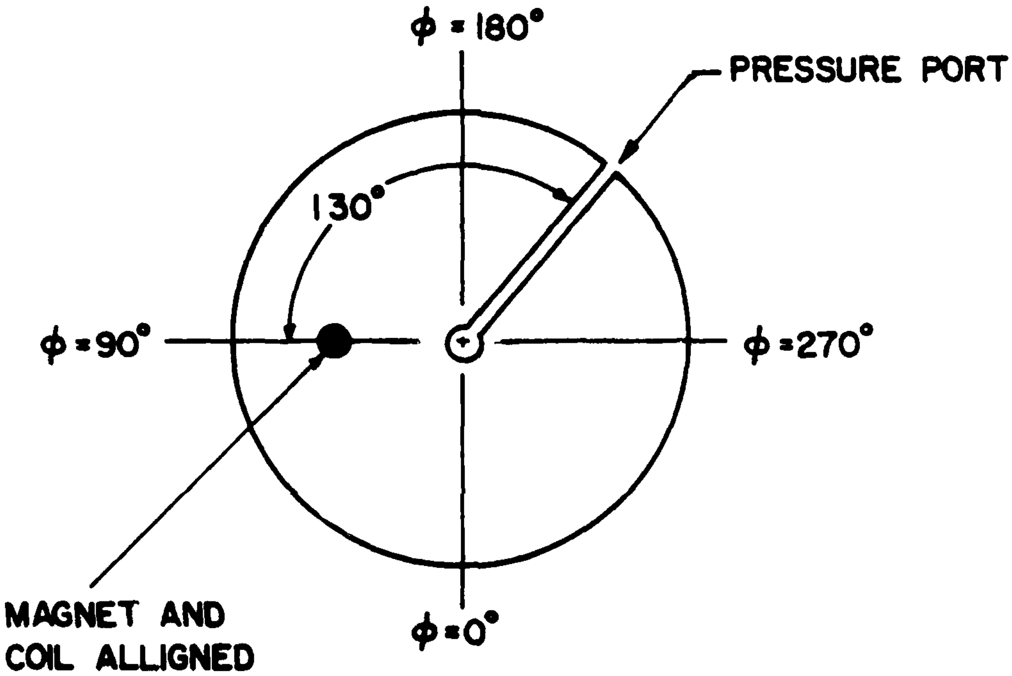

Figure 8. Location of coil and magnet with respect to the port to the 70 kHz pressure transducer in the wind tunnel reference system.

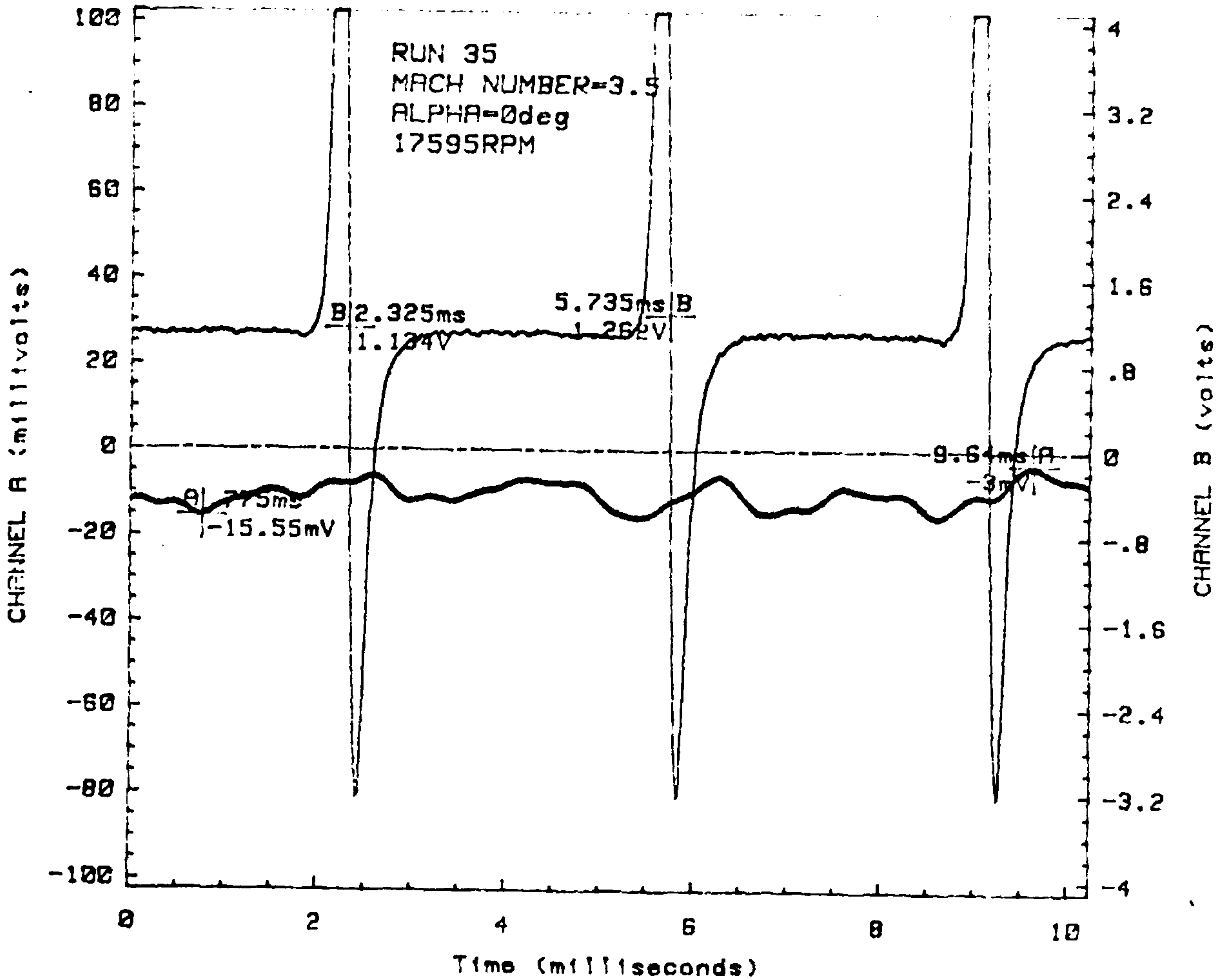

Figure 9. Raw voltages for pressure and spin at zero angle of attack and 17,595 RPM.

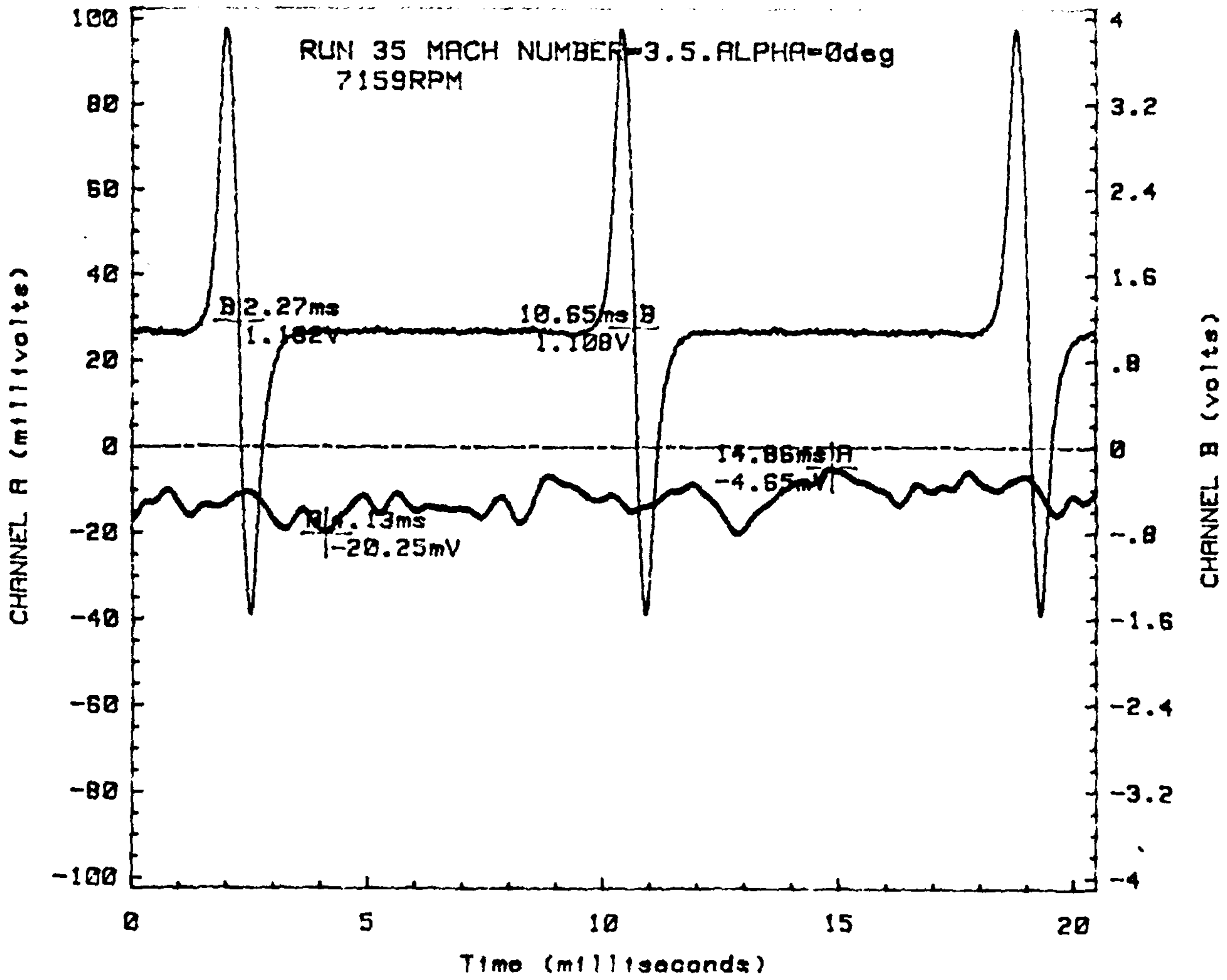

Figure 10. Raw voltages for pressure and spin at zero angle of attack for 7159 RPM.

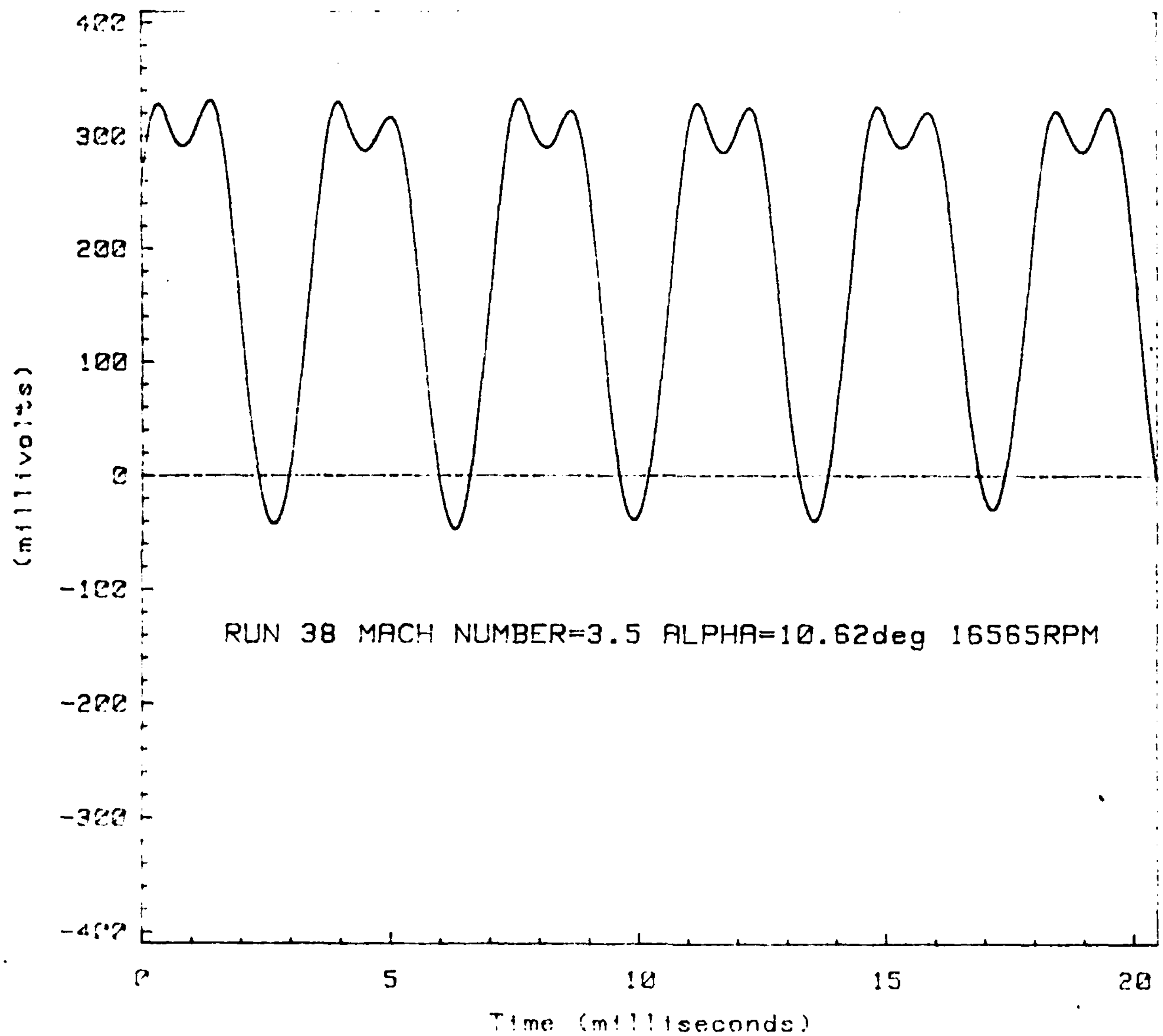

Figure 11. Raw pressure voltages for an angle of attack of 10.62 deg and Mach number 3.5

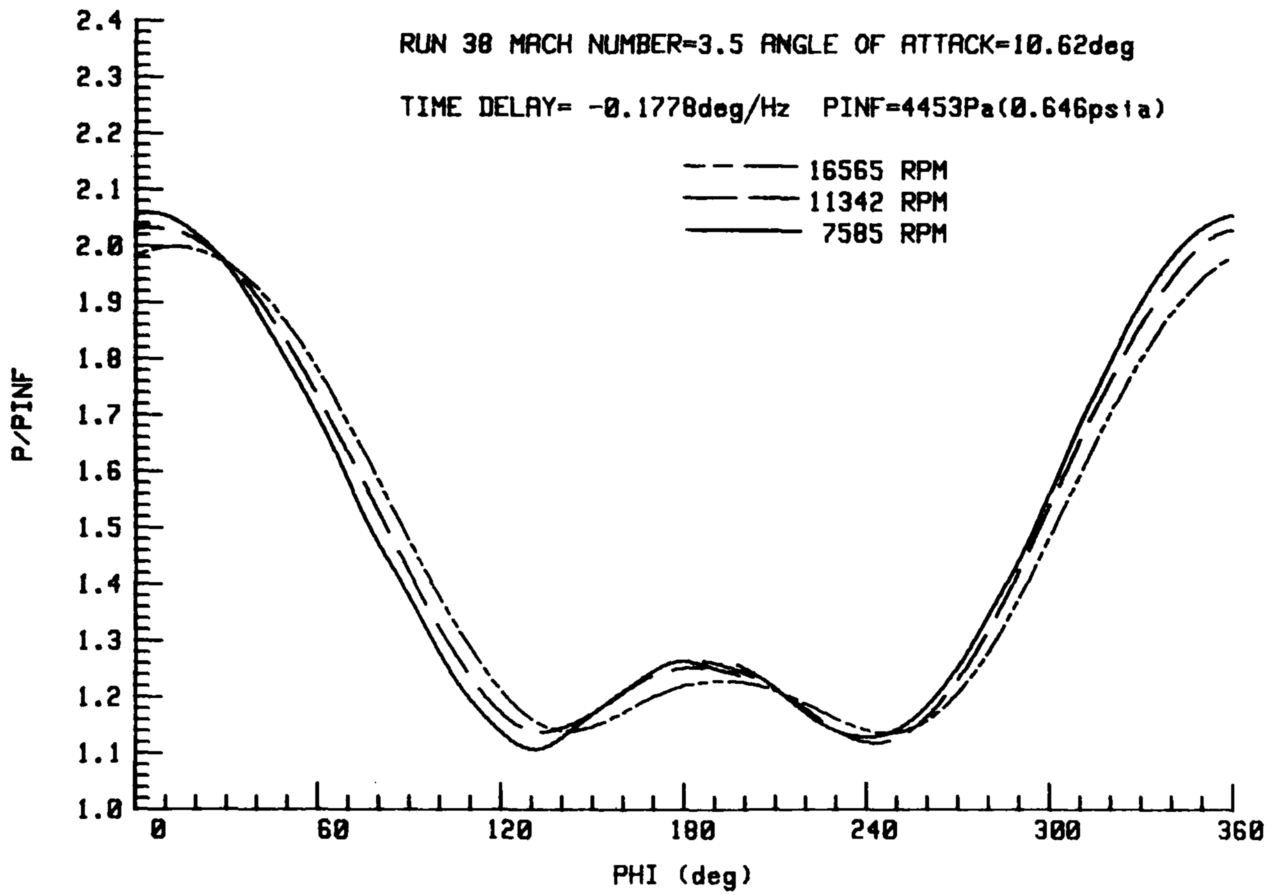

Figure 12. Superimposed pressure distributions for angle of attack of 10.62 deg, Mach number 3.5, and spins of 16,565 RPM, 11,342 RPM and 7,585 RPM.

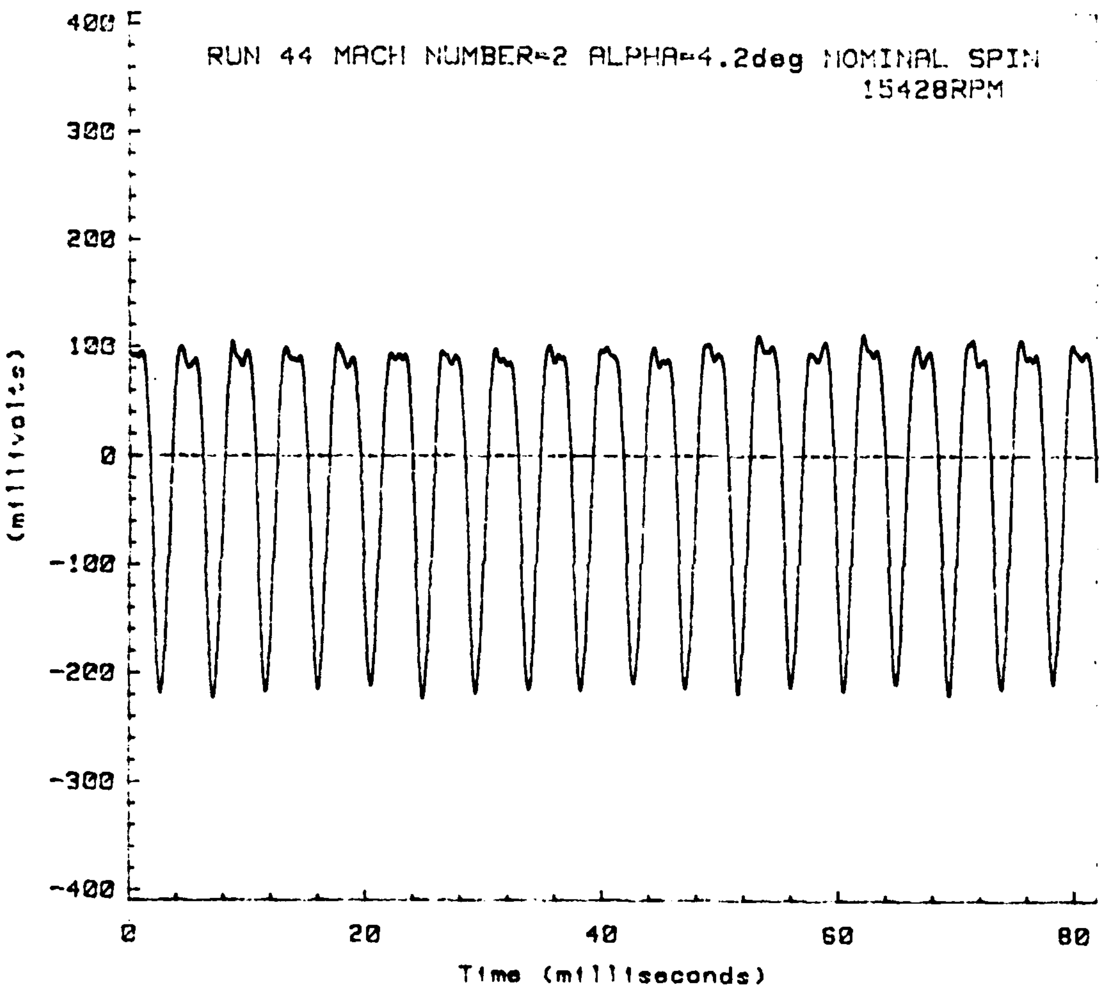

Figure 13. Raw pressure voltages for angle of attack of 4.2 deg and Mach number 2.0, and nominal spin of 15,428 RPM.

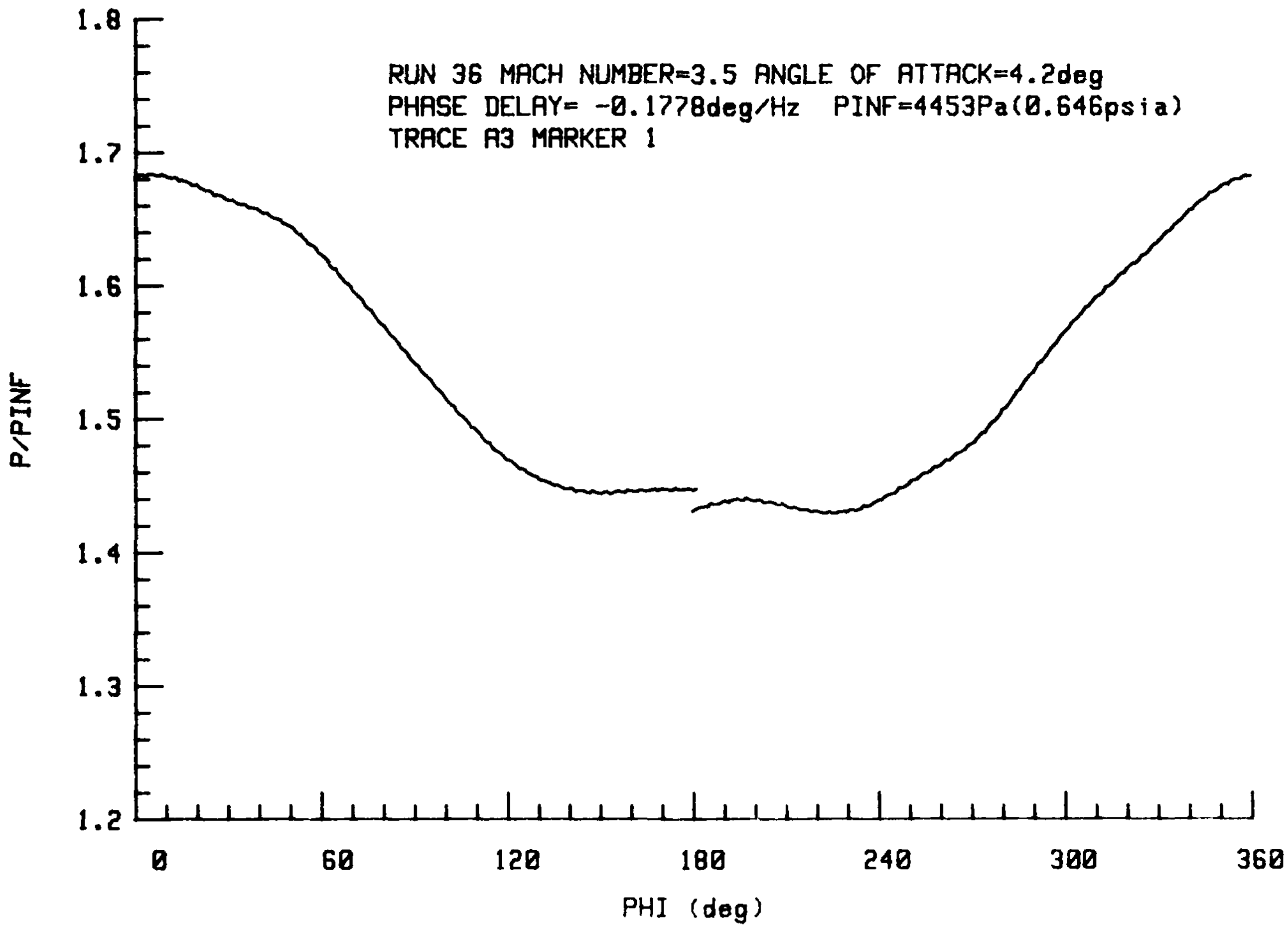

Figure 14. Pressure distribution for angle of attack of 4.2 deg, Mach number 3.5, and 13,544 RPM.

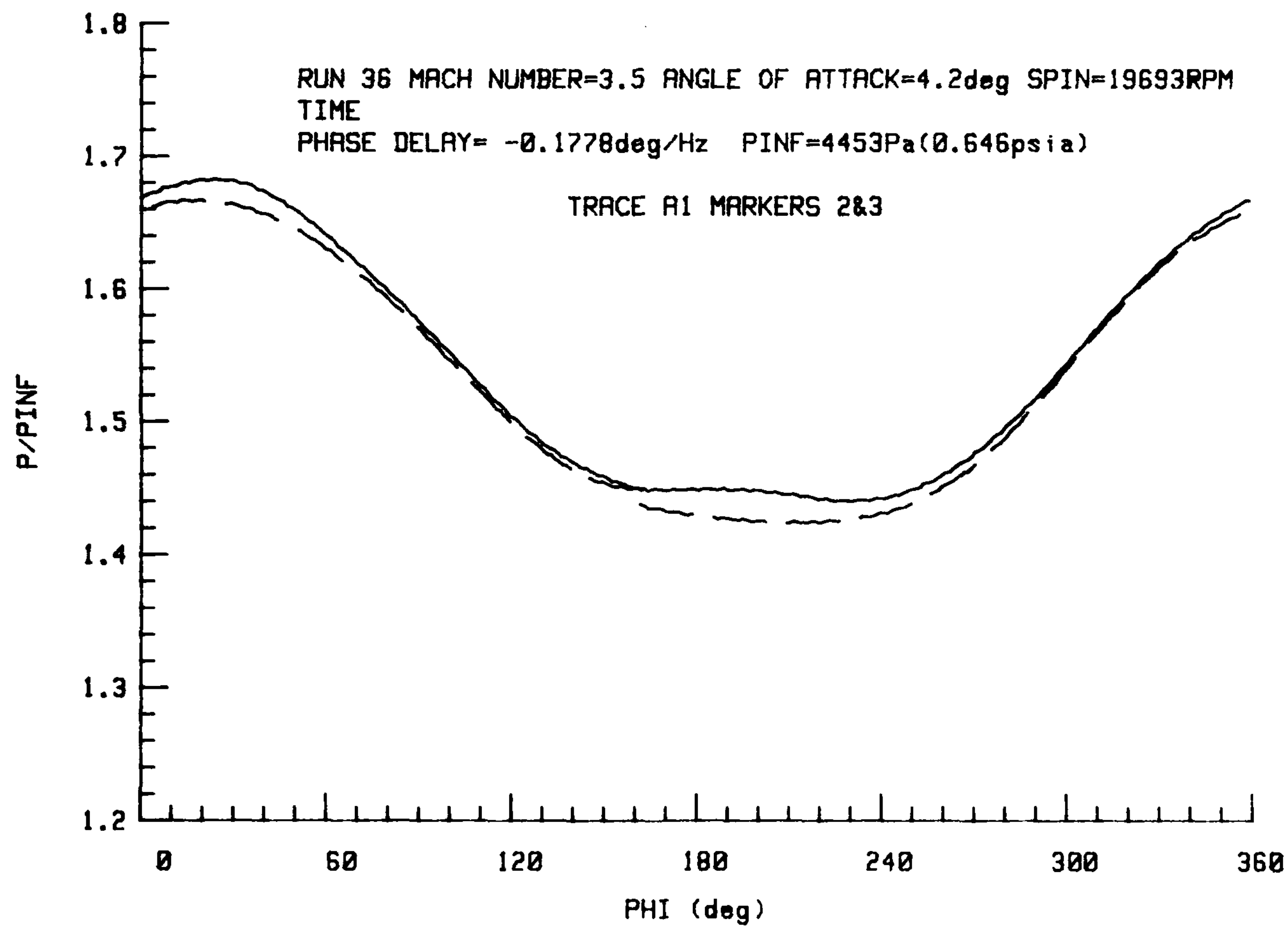

Figure 15. Pressure distribution for angle of attack of 4.2 deg, Mach number 3.5, and 19,693 RPM.

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